product of the present investigation and are useful chiefly for the practical purposes of indicating the intensity of radioactivity which may be produced for each of the isotopes under the conditions outlined in this paper. The nature of such targets, namely small amounts of powdered material, and the conditions of the bombardments were not such as to lead to sufficiently accurate cross sections to enable safe deductions to be made in regard to the mechanism of these relatively high energy nuclear reactions involving heavy nuclei.

However, it can be seen that the cross sections for the (d, n), $(d, 2n)$, $(d, 3n)$, $(d, 4n)$, etc., reactions on uranium in this energy range are substantially smaller than for the same reactions on non-fissioning nuclei. Apparently, a predominant fraction of the excited intermediate nuclei undergo the fission reaction. Consideration of the results suggest that the total cross section for the formation of neptunium isotopes by (d, xn) reactions does not change greatly over the energy range investigated, which suggests that increased excitation does not markedly increase fission and competing reaction yields at the expense of (d, xn) reaction yields.

It may be noticed that the reactions involving the emission of only a small number of neutrons, such as the (d, n) and $(d, 2n)$ reactions, do not drop off very much in yield even at relatively high deuteron energies. This indicates that reactions involving only small energy transfers[19] from the high energy bombarding particles are important here as has been found also to be the case for reactions with lighter nuclei. It may also be noticed that the lightest isotope, Np^{231}, is not formed in yields as high as the other isotopes at any deuteron energy, which perhaps indicates an increasing relative yield of the fission reaction with decreasing mass of the intermediate excited neptunium nuclei, as might be expected from the simple Bohr-Wheeler picture of the fission process.

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[19] R. Serber, Phys. Rev. **72**, 1114 (1947).

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Nuclear Mass Determinations from Nuclear Q-Values

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Consistent values of the masses of the light nuclei have been calculated from the best measurements of Q-values for several nuclear reactions, and from mass spectrographic measurements. Tables are given of the Q-values and of the calculated mass values.

1. INTRODUCTION

THE Q-values for several reactions involving light nuclei have been recently measured with probable errors of 20 kev or less. In general these measurements have been made possible through the employment of high resolution electrostatic or magnetic analyzers for determining the energy of the particles involved in the reaction. These new data are sufficient to determine the nuclear masses relative to H^1 through B^{10}, independently of mass spectroscopic data. Unfortunately sufficient data are not yet available to base the masses upon O^{16} and consequently the mass spectroscopic value for H^1 is used. Furthermore some uncertainty still exists in the mass of He^4 and subsequent nuclei as discussed below.

The mass values of H^1, D^2, C^{12} and N^{14} were calculated from the mass spectroscopic doublets $2H-D$, CH^4-O, CH^2-N^{14}, and $3D-C_{\frac{1}{2}}$. In view of the discrepancies recently found in the early values of $2H-D$, it was decided to use Nier's[1] recent values for the first three doublets combined with the results of Bainbridge[2] for the last doublet.* Nier's value for $2H-D$ combined with Bell and Elliott's[3] new value for $H^1(n, \gamma)D$ leads to an $n-H^1$ difference of 788 kev compared to 782 ± 1 kev as determined at Los Alamos from threshold measurements on $T^3(p, n)He^3$ combined with the decay energy of tritium. The nuclear data have been combined with the mass spectroscopic values of C^{12} and N^{14} to yield the masses of N^{13}, C^{13}, and C^{14}.

Table I lists all the accurately determined Q-values considered in this note. The $Li^7(p, \alpha)He^4$ value is not new but was included in order to determine the mass of the α-particle and hence it influences all subsequent

[1] T. R. Roberts and A. O. C. Nier, Phys. Rev. **77**, 746(A) (1950).
[2] K. T. Bainbridge, NRC Nuclear Science Series No. 1.
* It is emphasized that a future change in the mass spectroscopic value of H^1 will change the masses for D^2 to B^{10} inclusive by the same amount.
[3] R. E. Bell and R. G. Elliott (private communication).

TABLE I. Table of accurate Q-values.

Reaction	Q-measured	Adopted value of Q Mev	mMU*	Reference
$H^1(n, \gamma)D^2$	2.230 ±0.007	2.230	2.395	Bell and Elliott (priv. comm.).
$D^2(\gamma, n)H^1$	−2.186 ±0.004	−2.230	−2.395	NRC Nuclear Science Series No. 1.
$D^2(d, p)T^3$	4.036 ±0.022	4.032	4.330	Phys. Rev. **75**, 1947 (1949).
$D^2(d, n)He^3$	3.265 ±0.018	3.268	3.510	Phys. Rev. **75**, 1947 (1949).
$T^3(\beta^-)He^3$	0.0189±0.0005 0.0180±0.0186	0.0185	0.0199	Phys. Rev. **75**, 984 (1949). Phys. Rev. **76**, 853 (1949).
$T^3(p, n)He^3$	−0.7637±0.001	−0.7637	−0.8202	Phys. Rev. **76**, 325 (1949).
$He^3(n, p)T^3$	0.764 ±0.010 0.766 ±0.010	0.7637	0.8202	Phys. Rev. **75**, 1110 (1949). Phys. Rev. **77**, 641 (1950).
$Li^6(n, \alpha)T^3$	4.56 ±0.08** 4.92 ±0.03**	4.785	5.139	Phys. Rev. **75**, 782 (1949). Phys. Rev. **75**, 782 (1949).
$Li^6(p, \alpha)He^3$	4.017 ±0.022	4.021	4.319	Phys. Rev. **76**, 428 (1949).
$Li^6(d, p)Li^7$	5.006 ±0.016	5.012	5.383	Phys. Rev. **76**, 1766 (1949).
$Li^6(d, \alpha)He^4$	22.20 ±0.04	(22.292)	(23.942)	Phys. Rev. **56**, 548 (1939).
$Li^7(d, p)Le^8$	−0.193	−0.193	−0.207	Phys. Rev. **76**, 1766 (1949).
$Li^7(p, \alpha)He^4$	17.28 ±0.03	17.280	18.559	Phys. Rev. **56**, 548 (1939).
$Li^7(p, n)Be^7$	−1.6456 −1.6449±0.0016	−1.6453	−1.767	Phys. Rev. **75**, 246 (1949). Phys. Rev. **76**, 502 (1949).
$Be^8(\alpha)He^4$	0.089 ±0.005	0.089	0.0956	Phys. Rev. **76**, 428 (1949).
$Be^9(\gamma, n)Be^8$	$-\frac{2.230}{1.338}=-1.667$	−1.671	−1.795	Phys. Rev. **74**, 1225(A) (1949).
$Be^9(p, n)B^9$	−1.851 ±0.006 −1.8519±0.002	−1.8514	−1.9884	Phys. Rev. **65**, 33 (1944). Phys. Rev. **77**, 752(A) (1950).
$Be^9(p, d)Be^8$	0.558 ±0.003	0.559	0.600	Phys. Rev. **76**, 428 (1949).
$Be^9(p, \alpha)Li^6$	2.121 ±0.012	2.125	2.282	Phys. Rev. **76**, 428 (1949).
$Be^9(d, p)Be^{10}$	4.576 ±0.012	4.568	4.906	Phys. Rev. **76**, 1547 (1949).
$Be^9(d, \alpha)Li^7$	7.145 ±0.024	7.137	7.665	Phys. Rev. **76**, 1547 (1949).
$Be^{10}(\beta^-)B^{10}$	0.566 ±0.010	0.560	0.601	Phys. Rev. **76**, 183A (1949).
$B^{10}(p, \alpha)Be^7$	1.146 ±0.005	1.146	1.231	Phys. Rev. **76**, 587A (1949).
$B^{10}(n, \alpha)Li^7$	2.785 ±0.025	2.791	2.998	Phys. Rev. **74**, 1259A(1949).
$B^{11}(p, n)C^{11}$	−2.762 ±0.002	−2.762	−2.966	Phys. Rev. **77**, 752(A) (1950).
$C^{11}(\beta^+)B^{11}$	0.981 ±0.005	0.958	1.029	Proc. Roy. Soc. **A177**, 357 (1940-1941).
$C^{12}(d, p)C^{13}$	2.729 ±0.009	2.726	2.928	Phys. Rev. **76**, 1543 (1949).
$C^{12}(d, n)N^{13}$	−0.281 ±0.003	−0.279	−0.300	Phys. Rev. **75**, 1398 (1949).
$C^{13}(p, n)N^{13}$	−3.003 ±0.003	−3.005	−3.227	Phys. Rev. **77**, 752(A) (1950).
$C^{14}(p, n)N^{14}$	−0.620 ±0.009	−0.626	−0.672	Phys. Rev. **75**, 1 (1949).
$C^{14}(\beta^-)N^{14}$	0.156 ±0.001	0.156	0.168	NRC Nuclear Science Series No. 5.
$N^{13}(\beta^+)C^{13}$	2.222 ±0.003	2.223	2.387	NRC Nuclear Science Series No. 5.
$N^{14}(n, p)C^{14}$	0.616 ±0.010 0.630 ±0.006	0.626	0.672	Phys. Rev. **75**, 1110 (1949). Phys. Rev. **77**, 641 (1950).
$O^{16}(d, p)O^{17}$	1.925 ±0.009	1.925	2.067	Phys. Rev. **76**, 1543 (1949).
$O^{18}(p, n)F^{18}$	−2.455 ±0.002	−2.455	−2.637	Phys. Rev. **77**, 752(A) (1950).
$F^{19}(p, \alpha)O^{16}$	8.113 ±0.030	8.113	8.713	Phys. Rev. **78**, 88(A) (1950).

* 1 mMU = 0.9311 Mev.
** When corrected for the new range-energy relation [W. P. Jesse and J. Sadaushis, Phys. Rev. **78**, 1 (1950)], these results are close to the adopted value.

masses. The range of the α-particles from this reaction nearly coincides with the range of those from ThC′ and hence the measurement was considered to be more accurate than that of $Li^6(d, \alpha)He^4$ which if accurately known could also be used to determine the α-particle mass.

Among the data listed, there are eight independent cycles which determine the $n-H^1$ difference, the values ranging from 776±9 to 789±6 kev. The weighted mean of 782±1 kev is determined almost entirely by the Los Alamos data. Using this value the Q-values in each case were adjusted to be consistent with this difference. The adjustments made were weighted according to the experimental errors given and in no case did the change exceed 7 kev with the single exception of Townsend's value for $C^{11}(\beta^+)B^{11}$. Since the value of the $B^{11}(p, n)C^{11}$ threshold is very accurately known, the whole discrepancy of 23 kev in this case was ascribed to the

TABLE II. Table of atomic masses.

	From mass spectroscopic data	From nuclear data	Bethe	Δ (mMU)
n^1		1. 008 977	1. 008 930	+0.047
H^1	1. 008 137 4	*	1. 008 123	+0.014
D^2	2. 014 726	2. 014 719	2. 014 708	+0.011
T^3		3. 016 971	3. 017 02	−0.05
He^3		3. 016 951	3. 017 00	−0.05
He^4		4. 003 910	4. 003 90	+0.01
Li^6		6. 017 043	6. 016 97	+0.07
Li^7		7. 018 242	7. 018 22	+0.02
Li^8		8. 025 031	8. 025 02	+0.01
Be^7		7. 019 169	7. 019 16	+0.01
Be^8		8. 007 916	8. 007 85	+0.06
Be^9		9. 015 098	9. 015 03	+0.07
Be^{10}		10. 016 774	10. 016 77	0
B^9		9. 016 246	9. 016 20	+0.05
B^{10}		10. 016 173	10. 016 18	−0.01
C^{12}	12. 003 900	*	12. 003 82	+0.08
C^{13}		13. 007 554	13. 007 51	+0.04
C^{14}		14. 007 733	14. 007 67	+0.06
N^{13}		13. 009 941	13. 009 88	−0.04
N^{14}	14. 007 565	*	14. 007 51	+0.05
O^{17}		17. 004 515	17. 004 50	+0.02
F^{19}		19. 004 486	19. 004 50	−0.01

* Mass spectroscopic values used here.

$C^{11}(\beta^+)B^{11}$ determination. It was found that Townsend's measurement of $N^{13}(\beta^+)C^{13}$ was also some 20 kev different from two other precise measurements which agreed with each other. (See NRC Nuclear Science Series No. 5.) Consequently we have not included his results in adjusting the Q-values.

Finally, all other independent cycles among the reactions listed were considered. There are seven of these, and the Q-values in each case were adjusted in relation to the experimental errors to satisfy the cycles; in no case did this adjustment require a change of more than 9 kev, nor were any of the experimental errors exceeded. These *adopted* Q-values are listed in column 3 of Table I together with the reference. The values are given in Mev and in milli-mass units based upon 1 mMU=0.9311 Mev. These Q-values were then combined with the mass spectroscopic value for H^1 to yield the masses which are listed in Table II, while the mass spectroscopic data for C^{12}, N^{14} were also used to yield the masses of N^{13}, C^{13}, C^{14}. For comparison the values given in *Elementary Nuclear Physics* by H. A. Bethe are also listed together with the differences.

It is evident from the above that the reactions $Li^6(d, \alpha)$ and $Li^7(p, \alpha)$ should be accurately determined in a high resolution spectrograph in order to fix the α-particle mass. This would make the nuclear data satisfactory up to B^{10}. The H^1, D^2, C^{12}, O^{16} system is one of the basic mass spectroscopic cycles, and should be checked by nuclear methods. As mentioned earlier, the H^1 to D^2 part of this cycle now agrees with nuclear data, and the remaining two intervals D^2 to C^{12} and C^{12} to O^{16} offer two remaining checks on these data. C^{12} can be obtained from existing data if the two reactions, $B^{10}(d, p)B^{11}$ ($Q\sim 9$ Mev) and $C^{13}(d, \alpha)B^{11}$, ($Q\sim 5$ Mev), are determined accurately. Furthermore, the series $O^{16}(d, \alpha)N^{14}$ ($Q\sim 3$ Mev), $N^{14}(n, \alpha)B^{11}$ ($Q\sim -0.3$ Mev) and $B^{10}(d, p)B^{11}$ would connect B^{10} directly with O^{16}, but has the disadvantage of involving a neutron induced reaction with a negative Q. While the internal consistency of the nuclear data seems very good, a compounding of errors is certainly possible and comparisons with the mass spectroscopic values are very desirable.